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Carbon Dioxide Reduction Potential in Singapore's Power Generation Sector

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Abstract

The steady rise in energy demand is expected to continue in Singapore due to the country's economic and population growth. According to projections, electricity generation will increase by some 30% from 2010 to 2025. Despite the rise in demand, Singapore authorities have announced a commitment to reduce carbon emissions by 7-11% below 2020 business-as-usual levels, with a half of reductions coming from the power generation sector.
In this study, we examine the average carbon dioxide (CO_2) emissions or grid factor of power generation in Singapore, and aim to assess the carbon emissions reduction potential arising from different fuel and generation technology mixes. Adding alternative feedstocks and/or displacing existing generation technologies can have a wide range of consequences on the theoretical grid factor. We show that emissions savings can vary substantially depending on the type of fuel sources that are either added to the mix, or used to displace existing generation feedstocks. The results highlighted in this study provide a Singapore-specific example for targeting medium to longer-term emission savings from the power generation sector.

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Keywords: grid emission factors; future scenarios; carbon dioxide; CO_2; utilities; electrcicity; fuel mix

1. Introduction

Power generation in Singapore will continue to rely on fossil fuel in the next decades for several reasons: alternative energy sources can only be deployed in Singapore to a limited extent, nuclear power is not on the country's agenda in the near future, and electricity imports will not dominate the domestic

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energy landscape due to security reasons. Yet, several pathways to diversify the domestic fuel mix are being explored. The launch of LNG terminal operations in May 2013 indicated that natural gas will continue to feature in the future domestic use. The Renewable Energy White Paper, presented by the nation's Sustainable Energy Association in January 2014, showcased that by 2025 renewable energy can meet 8% of the demand in 2025. Finally, a coal-biomass power plant fueled by sub-bituminous coal was commissioned in 2012 to test the option of coal-fired generation.

In light of these recent developments, this study aims to investigate the average CO_2 emissions or grid factor of Singapore power sector for the reference year 2012, as well as CO_2 emissions reduction potentials of the alternative generation types mentioned – natural gas, renewables and coal – considering new capacity introduction up to year 2025.

2. Literature review

The methodology of estimating average and displaced greenhouse gas emissions (GHG) from electricity generation has been reflected in numerous past studies and reports [1], [2], [3], [4] . Among those, publications by IPCC and UNFCCC are almost excessively considered for studies of national emissions grid factors. Several papers discuss the topics of displaced and marginal emissions in large and complex electricity sectors like the US and UK [5], [6], [7]. The studies showcased that displacement effect of the added capacity can be different depending on how this capacity is introduced. Moreover, findings of these studies provide a good discussion basis on how marginal fuel types and power plants can be identified. For Singapore's case, past studies have dealt with the topic of GHG emissions from electricity generation [8], [9], [10]. The scope of these studies include either life-cycle emissions of one type of power plants, without accounting for the sector as a whole, or assume uniform performance characteristics for all systems. Finally, implications of future emissions from the local power sector have been reported by APEC and ERIA [11], [12]. However, little attention has been paid to the use of renewable energy and there is still a gap in research on emissions displacement for the local grid.

3. Methodology

The first part of the study deals with estimating the average CO_2 grid factor of the Singapore electricity grid. Emission factor calculation is based on reviewed methodologies (listed above), taking into account available data on local power plants, fuels and waste statistics. An accurate estimate has been possible because of the relatively small number of power generation plants and fuel types used. The second part of the study analyzes possible emissions displacements effects from four different generation scenarios. The scenarios were chosen based on recent reports, governmental announcements and expert opinions. Due to constraints in available data on targeted capacity growth, results are given in kg of CO_2/MWh. In such a way, a total amount of avoided emissions can be estimated by multiplying the value with the MW of displaced or added generation capacity.

3.1. Grid factor of the electricity system in Singapore

Carbon dioxide grid factor of the Singapore electricity system for the reference year 2012 was calculated according to the common methodologies suggested by IPCC and UNFCCC. CO_2 emissions depend on fuel amount consumed by power plants and the emission factor of the fuels. Fuel consumption can be estimated by dividing the net power output of 1 MWh by the product of heating value of fuel and thermal efficiency of the generating system. CO_2 emissions factors of fuels, unless published country-specific, can be found in literature. To estimate the grid factor more accurately, we calculated fuel consumption and CO_2 emissions for every licensed power plant in Singapore and used this information to obtain the average grid factor.

3.2. Review of fuels and technologies used for power generation in Singapore

A total of three fuel types including natural gas (78.7%), petroleum products, almost all of which is fuel oil (19%) and waste incineration/waste-to-energy or WTE (2.3%) were considered for the reference mix in 2012. Calorific values and CO_2 emissions factors of the first two types were obtained from the most recent IPCC survey. Country-specific information about composition and calorific values of the disposed municipal waste was collected from the Singapore waste statistics and other relevant literature sources [13], [14], [15].

Accurate information about efficiencies of operating systems is important for the purpose of estimating of fuel consumption and related CO_2 emissions. In Singapore, the major share of generation stock uses F-class combined-cycle gas turbine (CCGT) technology fueled by natural gas. Other than that, the power sector relies on steam turbines to utilize fuel oil and waste as well as on a small share of open-cycle gas turbines (OCGT). Based on the literature review and the information from generation companies' websites, we identified four types of CCGT with nominal (clean-as-new, 100% load condition) efficiencies indicated: Alstom GT-6 (58.3%), Mitsubishi M701F (57.5%), Siemens 4000F (58.4%), General Electric 9FB (58.0%). Steam turbines running both on fuel oil and waste were assumed to have nominal efficiency of 35% and open-cycle gas turbines 30% [16].

In practice, generating systems rarely achieve their listed nominal efficiencies for various reasons. Possible loss in performance happens due to equipment deterioration, impacts of ambient conditions and operational practices. In our study, we quantified these effects for each operating power plant according to the relevant technology type and age. Equipment deterioration inside the power plant occurs naturally even if the system is regularly maintained. We assumed for all turbine types the average decline in efficiency of 2% after the first five years of operation, followed by 1% reduction over every next five-year span [17]. Higher temperatures of ambient air and cooling water and lower air pressure due to altitude can cause additional penalties on power plant performance. In Singapore-specific case, only the ambient temperature should be considered, because of its low geographic altitude. Based on the literature review, we applied a 2.2% efficiency loss due to ambient temperature. Finally, the load factor plays an important role in estimating of turbine performance. For Singapore, the average plant load factor of 70% was applied based on the historical capacity factor of the existing Class F technology [16], [18], [19].

A case study below illustrates how performance characteristics are determined for a CCGT plant commissioned in 2001:

[Operating efficiency in 2012] = [Clean-as-new efficiency, Alstom GT6] * [age penalty,10 years] * [impact of ambient conditions] * [impact of part-load, 70%] = $0.583*0.970*0.978*0.970 \approx 0.536$ (Eq. 1)

3.3. Utilization of capacity and scenario assumptions

In order to accurately estimate the grid factor of an electricity system, it is important to know the average production share of every unit in the system. In Singapore, power plants are dispatched according to their cost of production (merit order). A case-specific statistics about cost of production and dispatch parameters was not publically available for Singapore. Therefore, we assumed that power plants contribute to the grid proportionately to their operating efficiency and there are no must-run plants. Due to fact that operating efficiency reflects the fuel consumption, it can also be related to the cost of generation. However, it must be noted that this assumption is limited, as it does not account for fuel costs and actual dispatch regulations. For example, gas turbines may be preferred when flexible dispatch is needed despite their low efficiency and high generation cost. Another example is burning of waste which may occur independently from the actual demand in the grid.

The CO_2 displacement effects of four alternatives are considered: R (any form of renewable energy), C (coal, supercritical technology), RC (50/50 tandem of renewable and coal), H (new generation of CCGT). Scenario R was assumed to be carbon neutral; for the scenarios C and G, emission factors were calculated as in 3.1 based on operating efficiencies of 47% (C, RC) and 60% (G). Corresponding emission factors were found to be 736 kg, 368 kg and 341 kg of CO_2/MWh. The results were plotted against average emissions factors for each generation type and maximal factors of marginal petroleum and CCGT units.

3.4. Results

Table 1 shows average CO_2 emissions of Singapore electricity sector for the reference year 2012. The values for various generation types range from 384 kg CO_2/MWh for CCGT to 808 kg CO_2/MWh for petroleum-fired ST. The average grid emission factor for the operating margin was estimated at 486 CO_2/MWh which is consistent with officially published values [20], [21]. According to sensitivity analysis, changing power plant efficiency by 1 pt affects emissions by ±6 kg CO_2/MWh (CCGT) up to ±35 kg CO_2/MWh (WTE).

Table 2 depicts potential CO_2 displacement with the use of alternative fuels or technologies. Each cell contains the difference between emissions rates in kg CO_2/MWh achieved by replacing an existing generation system (column) with an alternative (row). Columns "$CCGT_{max}$" and "$Petroleum_{max}$" contain estimated marginal units which should be prioritized for capacity displacement. Column "2012" contains the difference in emissions rates if 1 MWh of the typical 2012 power generation fuel mix was replaced by the alternative source.

Generation type	Proportion in generation mix 2012, %	Average operating efficiency,%	CO_2 emissions factor of fuel, kg CO_2/MWh	Emissions, kg CO_2/MWh	Effect of ±1 pt th.eff. change, kg CO_2/MWh
NGas-OCGT	**n/a**	**27.3**		**739**	**±24**
NGas-CCGT	**n/a**	**52.6**	**202.0**	**384**	**±6**
Natural gas total	**84.3**	**n/a**		**427**	**n/a**
Petroleum	**12.3**	**31.7**	**278.6**	**808**	**±26**
Municipal waste	**3.4**	**18.8**	**148.0**	**788**	**±35**
Renewable	**0**	**n/a**	**0.0**	**0**	**n/a**
Sub-bitumn. coal	**0**	**47.0**	**345.9**	**736**	**±16**
Total	**100**	**n/a**	**n/a**	**486**	**n/a**

Table 1. Fuel mixes, efficiencies and CO_2 emissions factors in Singapore power sector

	Gas-OCGT	Gas-CCGT	$CCGT_{max}$	Petroleum	$Petroleum_{max}$	WTE	Coal	2012
Renewable	-739	-384	-397	-808	-814	-788	-736	-486
Clean coal	-3	352	339	-72	-77	-52	0	250
Renewable/Clean coal	-371	-16	-29	-440	-445	-420	-368	-118
H-class CCGT	-402	-47	-60	-471	-477	-451	-399	-149

Table 2: CO_2 Emissions reductions potentials in Singapore power sector

3.5. Conclusions

The carbon grid factor of the electricity sector in Singapore is currently low compared to those of other countries in Asia [22]. This is due to the heavy reliance on cleaner natural gas for power generation in Singapore. Because Singapore has limited potential for renewable energy penetration, choosing CCGT for the baseload power may serve as an example for countries that aspire to reduce emissions in the power sector but deal with similar constraints.

Furthermore, CO_2 reductions can be achieved through the scenarios R and G followed by the scenario RC. Supercritical coal technology is a viable source of emissions reductions only if it is used to displace fuel oil. When considering the existing fuel mix, the largest potential exists for displacing oil-fired systems which have high carbon footprint and a sizeable share in the total mix. WTE systems are unlikely to be displaced because their electricity output is only a side product of waste treatment. Reduction potentials of added capacity by type would vary depending on how much MWh are added to the total mix and subject of further study.

According to projections, renewable energy could make 8% of the total energy mix in Singapore in 2025 where the annual electricity generation could be 59.4 TWh [21], [12]. Therefore, using renewables could help to reduce 1,824 to 3,864 kt of CO_2 annually, depending whether CCGT or oil-fired capacity is displaced. Adopting RC, H to 8% extent of the total mix would result in savings between 76 to 2,115 kt (RC) and 225 to 2,264 kt of CO_2 (G). Replacing oil-fired or CCGT generation with 8% of coal-fired can result in between 366 kt of avoided or 1,673 kt of added CO_2 emissions.

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